Discovery of exceptionally strong electron-capture transition sheds new light on the fate of intermediate-mass stars

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on behalf of
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Electron-capture rate on $^{20}\text{Ne}$

- Intermediate-mass stars after C burning = degenerate O-Ne core

- Electron-capture rates:
  2nd forbidden transition can play a role for the most relevant densities
Measurement idea

• Measure 2nd forbidden decay of $^{20}\text{F}$ to $^{20}\text{Ne}$ ground-state

• Previously only upper limit known

\[ i_{1/2} = 11.0062(80) \text{ s} \]

\[
\begin{align*}
\beta & \quad < 7 \times 10^{-7} \\
& \quad < 1.5 \times 10^{-6} \\
& \quad 8.2(6) \times 10^{-5}
\end{align*}
\]

\[
\begin{align*}
\beta & \quad 5.788 \\
& \quad 5.621 \\
& \quad 4.967
\end{align*}
\]

\[ 0.999907 \rightarrow 1.634 \rightarrow 0.0 \]

\[ \sim 1 \times 10^{-5} \]

\[ 0^+ \]

\[ 2^+ \]

\[ 1^- \]

\[ 3^- \]

\[ 2^- \]
Why is it difficult?
The decay experiment

- Radioactive $^{20}$F$^+$ beam at IGISOL-4 / JYFL Accelerator Laboratory
  - $(d,p)$ on BaF$_2$, $^{12}$B (from B) for calibration
  - 30 kV transport, stopped in thin C foil
  - Intensity around 11 kHz

- Magnetic transporter
  - Selects momentum range

- Plastic-scintillator
  - 3 parts: veto, front, main:
Counts / hour / 100 keV

- $^{40}$K $\gamma$
- $^{208}$Tl $\gamma$
- $^{222}$Rn $\alpha$
- CR $\mu$
- CR secondaries

$E_\beta$ (MeV)
Recorded beta spectra

- At 67.7% max current - background (Pyhäsalmi mine)

Veto cut = no signal in Veto
Front cut = deposited energy 0.65-1.60 MeV in Front

ISOLDE Workshop and Users meeting, December 2019
Fit to beta spectra

Maximum likelihood fit - - $\chi^2/N = 133.6/112$
Ground state transition $^{20}\text{F}$ to $^{20}\text{Ne}$

• Calibrations cross-checked with $^{12}\text{B}$, $^{207}\text{Bi}$ ... validated with GEANT4

• Branching ratio: $(0.41 \pm 0.08 \pm 0.07) \times 10^{-5}$

• $\log(ft) = 10.89(11)$, strong second-forbidden non-unique transition

• Several shell-model calculations (IM-SRG, CCEI, USDB) agree within a factor of 2
Deduced electron-capture rate on $^{20}\text{Ne}$

- Intermediate-mass stars after C burning = degenerate O-Ne core

- Electron-capture rates:
  gs transition plays an essential role
Brief results of stellar modelling

• New gs rate: electron capture on $^{20}$Ne proceeds at lower densities

Simulations:
thermonuclear explosion rather than gravitational collapse
Contributors to the work
Contributors to the work

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Measurement of the $2^+ \rightarrow 0^+$ ground-state transition in the $\beta$ decay of $^{20}$F

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Author Contributions The project was born out of discussions between KL, GMP and HOUF. OSK led the experiment, analyzed the data and wrote the paper together with SJ, DFS, GMP, KL and FR; all authors were involved in the project and commented on the paper. DFS and HM performed the MESA simulations. SJ performed the LEAFS simulations with assistance from STO. The electron-capture rates were calculated by DFS, GMP, KL, AI and BAB. The experiment was carried out by OSK, MH, AK and SRA under the supervision of WHT and with assistance from TE, AJ, IM, HP and JÅ. Finally, HOUF and KR helped with the data analysis.

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Extras
Gamma spectra

LaBr$_3$(Ce) detector
Modelling extras

FIG. 4. Mass ($M$) of bound remnant and ejecta and mass fractions ($X$) of oxygen + neon and iron-group elements in the remnant are shown as a function of the central density at ignition ($\rho_c^{\text{ign}}$). Filled markers denote simulations with central ignition; empty markers denote simulations with ignition occurring in a sphere with radius of 50 km.

FIG. 5. Mass fraction relative to solar, $X/X_\odot$, of stable isotopes in the ejecta of the (off-center) thermonuclear explosion compared to the gravitational collapse of Ref. [45].
Shape of beta spectrum

- Depends on detailed matrix elements...